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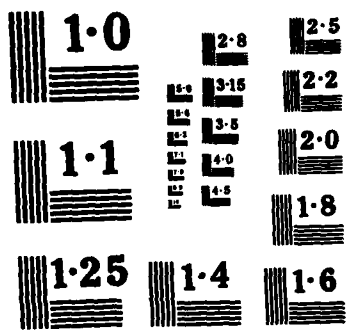


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# EXPERIMENTAL AND THEORETICAL STUDIES OF LASER PROPULSION PHENOMENOLOGY

Final Technical Report

For the Period

15 January 1984 - 28 February 1985

By

D. Rosen, G. Caledonia, N. Kemp, R. Krech, and L. Cowles

March 1985

Sponsored by

Air Force Office of Scientific Research (AFSC)
Bolling Air Force Base
Washington, DC 20332

Under Contract No. F49620-83-C-0039



PHYSICAL SCIENCES INC.
RESEARCH PARK, ANDOVER, MA 01810



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Physical Sciences Inc.
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This report summarizes progress on a research program carried out to investigate and define physical process important to the operation of pulsed and CW laser-heated thrusters. The work performed in this 2-year effort involved two tasks: one dealing with issues related to laser energy absorption in a pulsed thruster and the other dealing with issues related to laser energy absorption in a CW thruster.

For the pulsed studies, the first year's effort involved theoretical and experimental investigations of the threshold requirements for achieving laser-induced gas breakdown at short wavelengths (≤ 1 micrometer). With these breakdown studies completed, the next step, initiated in the second year, was


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19. ABSTRACT (Continued)

to determine the degree of pulsed laser energy absorption that can be achieved in the laser-initiated plasma. Toward this end pulsed laser energy deposition studies were performed using a pulsed Nd:glass laser as the energy source (wavelength = 1.05 micrometers, pulse duration = 20 ns) and high pressure hydrogen and argon gases as the absorption media. The percentage of laser energy absorbed in the laser-produced plasma was determined from measurements of the fraction of laser energy transmitted through the breakdown region as well as from optical interferometric measurements to determine the strength of the laser-produced blast wave. The initially deposited energy was inferred from the measured blast wave trajectories by comparing them with predicted trajectories calculated by a detailed hydrodynamic model. Results are presented for the energy deposition efficiency achieved in argon and hydrogen as a function of initial gas pressure (0.3 atm $\lesssim$ P $\lesssim$ 10 atm).

The CW studies have involved investigations of the absorption properties of potential high temperature molecular absorbers over the temperature range of 1000 to 3500 K and at $CO_2$ (~10 micrometers) and DF (~(4 micrometers) laser wavelengths. The measurements are performed behind incident and reflected shock waves. Species studied to date include $H_2O$, $CO_2$, $NH_3$, $SF_6$, and $NF_3$. Small signal (linear) absorption coefficients have been measured for these species (including effects due to dissociation fragments). These measurements have been performed under pressure and temperature conditions, and within non-equilibrium chemical kinetic regimes, appropriate to the propulsion application. In addition, observations of saturation phenomena in the intensity range of $10^3$ to $10^6$ W/cm$^2$ have been performed at $CO_2$ laser wavelengths for the species $SF_6$ and $NH_3$.

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## 1. RESEARCH OBJECTIVES

Laser propulsion, in the present context, refers to the beaming of energy from a remote high power laser to a rocket engine. This power is absorbed in a working fluid in the engine, and converted into kinetic energy of the fluid to produce thrust.

This idea was first proposed in 1971 by Arthur Kantrowitz, and published in May 1972.[1.1] It introduces a new type of rocket, which combines the high specific impulse (greater than 1000 s) of ion propulsion with the high thrust to mass ratio of chemical propulsion, a combination not achievable by any other practical propulsion system as yet known. This unique combination of advantages is made possible by the high temperatures which can be reached, and by the reduced weight of the propulsion system. The temperatures are not limited by chemical flame temperatures, but only by the ability to focus, absorb and contain the laser beam energy. The reduced weight is a result of the remote power source, whose mass does not have to be transported with the rocket.

While laser propulsion is a very attractive idea for improving the performance of rockets, it clearly requires a great deal of study before it can be converted to an actual propulsion system. If we focus on the rocket engine component of the laser propulsion system, we can identify four general processes which occur. A high energy laser beam must be introduced into the rocket, the laser energy must be absorbed by the gas, the resulting hot gas must be confined, and the thermal energy must be converted to directed kinetic energy.

Research on laser-heated thrusters has been pursued under NASA and DARPA sponsorship for a number of years. Each of these agencies has concentrated on one of the two types of laser propulsion which has been proposed. Continuous wave (CW) propulsion (Figure 1) uses the power from a steady laser beam to heat a gas in the absorption chamber. The gas is then expanded out a nozzle in a conventional manner to produce thrust. Repetitively pulsed (RP) propulsion (Figure 2) uses the power from a pulsed laser beam to create periodic "explosions" in cold gas downstream of the nozzle throat, by rapidly

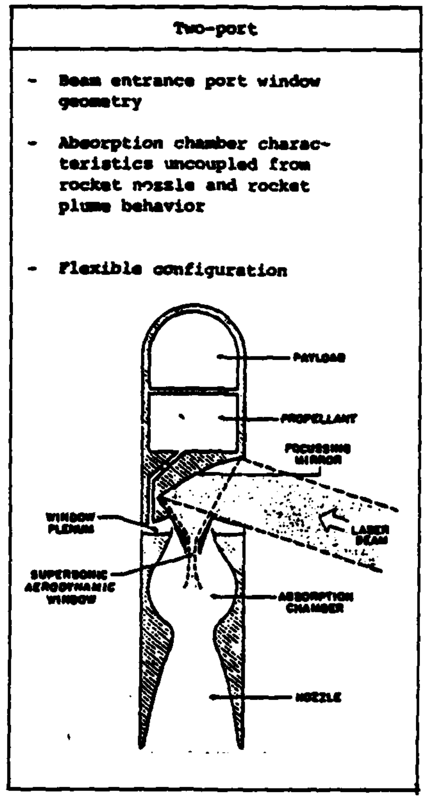


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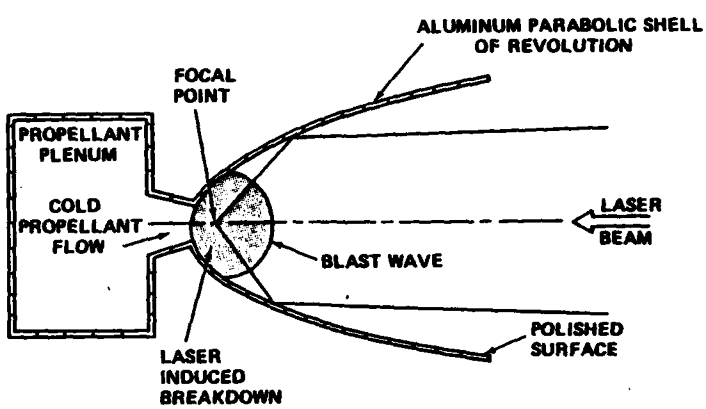
Figure 1. Schematic diagram of a CW laser rocket




- PROPULSION SEQUENCE
  - COLD PROPELLANT FLOWS THROUGH THROAT
  - LASER ENERGY ABSORBED VIA INVERSE BREMSSTRAHLUNG DOWNSTREAM AT FOCUS
  - SHOCKED GAS EXPANDS OUT NOZZLE
  - SEQUENCE REPEATS: PROPELLANT USE CONTROLLED BY MASS FLOW AND LASER REPETITION RATE

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Figure 2. Schematic of repetitively pulsed laser-powered thruster

depositing the laser energy into the gas via laser-induced gas breakdown followed by laser/plasma absorption. The resulting blast wave imparts high velocity to the gas, creating thrust as it expands out the nozzle.

A general overview of laser propulsion was given in 1978, Ref. 1.2. The present state of knowledge of the physics of laser-heated rockets has recently been summarized by PSI in three position papers, covering the areas of CW propulsion, RP propulsion, and laser energy absorption.[1.3]

This report describes the results of experimental and theoretical studies directed toward resolving technical issues critical to the ultimate development of both continuous wave (CW) and repetitively pulsed (RP) laser propulsion devices. The research was supported by the Air Force Office of Scientific Research, Directorate of Aerospace Sciences.

The investigations performed during this second year effort have involved a two-prong approach with investigations into both CW and pulsed laser thruster phenomenology. The research related to CW propulsion has involved experiments to determine the absorption properties of selected molecular absorbers of CW $CO_2$ (~10.6 μm) and DF (~3.8 μm) laser radiation over the temperature range of ~1000 to 4000 K. Such molecules could be added in low concentrations to hydrogen to absorb laser radiation via vibration-rotation band transitions. The investigations in support of pulsed thruster technology development have involved performing experimental studies and supporting model calculations to determine the degree of pulsed laser energy deposition that can be achieved in selected propellant gas candidates. A Statement of Work describing these efforts is given in Figure 3.

A substantive summary of the significant accomplishments and progress made in the last 12 months toward achieving the above research objectives is presented in Section 2 of this document. A summary of the accomplishments achieved during the first year's effort can be found in Ref. 1.4 with more scientific details available in Ref. 1.5.

1. Extend measurements of the low irradiance absorption coefficients to selected molecular absorbers (and their dissociation fragments) of DF laser radiation (3.8 micrometer). These measurements will be performed using a DF laser probe with line selection capability and will span the temperature range of 1000 to 4500 K. Effects due to collision density and foreign gas broadeners will be examined. (Extension of Tasks 1 and 2 in 0001AA.)

2. Design and carry out experiments to measure the saturation characteristics of selected molecular absorbers at irradiances between $10^3$ to $10^5$ W/cm$^2$. These measurements will be performed in a shock tube using pulsed DF and $CO_2$ laser probes and will span the temperature range of 1000 to 4500 K. Effects due to collision density will be investigated where warranted. (Extension of Task 3 in 0001AA.)

3. Perform a theoretical and experimental study of plasma absorption of short wavelength laser radiation. Measurements of the transmission of 1.06 and 0.53 micrometer laser light pulses through laser produced plasmas of rare gases and nitrogen will be performed. Separate diagnostics will be employed to measure scattering losses. Total deposited laser energy will also be inferred from separate measurements of the strength of the laser-induced blastwave. The model will include evaluation of all potential absorption mechanisms and consider the dynamics of plasma growth and the propagation dynamics of the gas absorption front. The model will be exercised against the experimental data base.

Figure 3. Statement of Work for current research effort

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## 2. STATUS OF RESEARCH EFFORT

### 2.1 Linear and Saturated Absorption of Laser Radiation in Heated Molecular Gases

The physical processes involved in heating the working fluid of a rocket engine with a high power CW laser beam can be simply described. The gas is injected into the stagnation/absorption zone at a temperature most probably determined by regenerative cooling requirements. As the gas flows toward the throat it is heated by absorption of laser radiation. With hydrogen as the primary propellant constituent, the equivalent of nine 10.6 μm photons per molecule must be absorbed to reach a stagnation condition that yields a specific impulse of ~1000 s.

The absorption scheme originally considered required the laser-induced breakdown of the $H_2$ "fuel" followed by the formation of a stable laser-supported combustion (LSC) wave. The principal absorption mechanism in this case is inverse electron bremsstrahlung which requires significant ionization levels in the gas. For pure $H_2$, ionization becomes significant at ~10,000 K with the development of a stable LSC wave requiring temperatures of ~20,000 K. It has been suggested that the introduction of alkali seeds, which will begin to thermally ionize at temperatures of ~3000 to 3500 K, would allow operation at temperatures of <10,000 K, thus providing a less severe thermal environment for thruster design.

Although the use of alkali seeds appears promising, an LSC wave mechanism is required to heat the gas to T ~3000 to 3500 K to initiate alkali ionization. Alternatively, other "seed" molecules can absorb the laser radiation via vibration-rotation band transitions. Such absorbing molecules can provide for gas heating to temperatures of ~3000 to 3500 K, so that heating from the initially "cold" gas to stagnation conditions can be continuous rather than through laser-induced breakdown. Furthermore if such species can absorb to T ≈4500 to 5000 K, then specific impulses of 1000 to 2000 s can be achieved without the need for ionization (and thus alkali seeds.)

The present program has been directed towards studying the absorption properties of potential "high temperature" molecular absorbers over the temperature range of 1000 to 3500 K and at $CO_2$ (~10.6 μm) and DF (3.8 μm) laser wavelengths. These measurements have been performed behind incident and reflected shock waves. Species studied to date include $H_2O$, $CO_2$, $NH_3$, $SF_6$, and $NF_3$. Small signal (linear) absorption coefficients have been measured for these species (including effects due to dissociation fragments). These measurements have been performed under pressure and temperature conditions, and within non-equilibrium chemical kinetic regimes, appropriate to the propulsion application. In addition, observations of saturation phenomena in the intensity range of $10^3$ to $10^6$ W/cm$^2$ have been performed at $CO_2$ laser wavelengths for the species $SF_6$ and $NH_3$.

The absorption measurements have been performed in the PSI 1.5 in. shock tube facility which provides a steady environment of heated gases for test times of several hundred microseconds. A 5 W CW $CO_2$ probe laser was used in the dual beam mode to perform the small signal absorption measurements. Saturation studies were also performed in the dual beam mode using a 10 J pulsed $CO_2$ laser introduced into the shock-heated gases colinear with the CW laser. The transmission of the pulsed laser was monitored with a separate detector with the CW and pulsed beam separation being effected through the use of a Brewster polarization splitter.

Absorption measurements were performed behind both incident and reflected shock. Gases studied in this years effort included $SF_6$, $NF_3$, and $NH_3$. A summary of the test conditions is provided in Table 1.

$SF_6$ was studied for several reasons: 1) it is perhaps the most efficient gaseous absorber of $CO_2$ laser radiation, 2) previous measurements[2.1] of the temperature dependent $SF_6$ absorption coefficients, albeit at subatmospheric pressure, are available for comparison with the present results; and 3) $SF_6$ is a classic saturable absorber which has attracted considerable study at low pressures.[2.2,2.3]

TABLE 1

Current Experimental Studies

| |
|---|
| $SF_6$ ($6 \times 10^{-4}$ in Ar) |
| P = 10 to 70 atm |
| T = 500 to 2500 K |
| P(20), P(24), P(28) lines |
| Room temperature saturation studies |
| $NF_3$ (3% in Argone) |
| P = 17 to 70 atm |
| T = 500 to 2100 K |
| P(20) line |
| $NH_3$ (9.4% in Ar, 5% in $H_2$/Ar) |
| P = 10 to 40 atm |
| T = 900 to 2900 K |
| P(20) line |
| Saturation studies |

Typical results for the small signal absorption coefficient of $SF_6$ at the P(20) $CO_2$ laser line are shown in Figure 4. The absorption coefficient decreases with increasing temperature. This is expected inasmuch as the spectral extent of the $SF_6$ $\nu_3$ band shifts to the red, away from the laser transition, as temperature increases. The data of Nowak and Lyman[2.1] are shown for comparison and the agreement can be seen to be quite good. Note that in equilibrium $SF_6$ would be fully dissociated at temperatures exceeding 500 K. The slowness of the finite rate $SF_6$ chemistry allowed us to measure the predissociation absorption coefficient to temperatures above 2000 K.

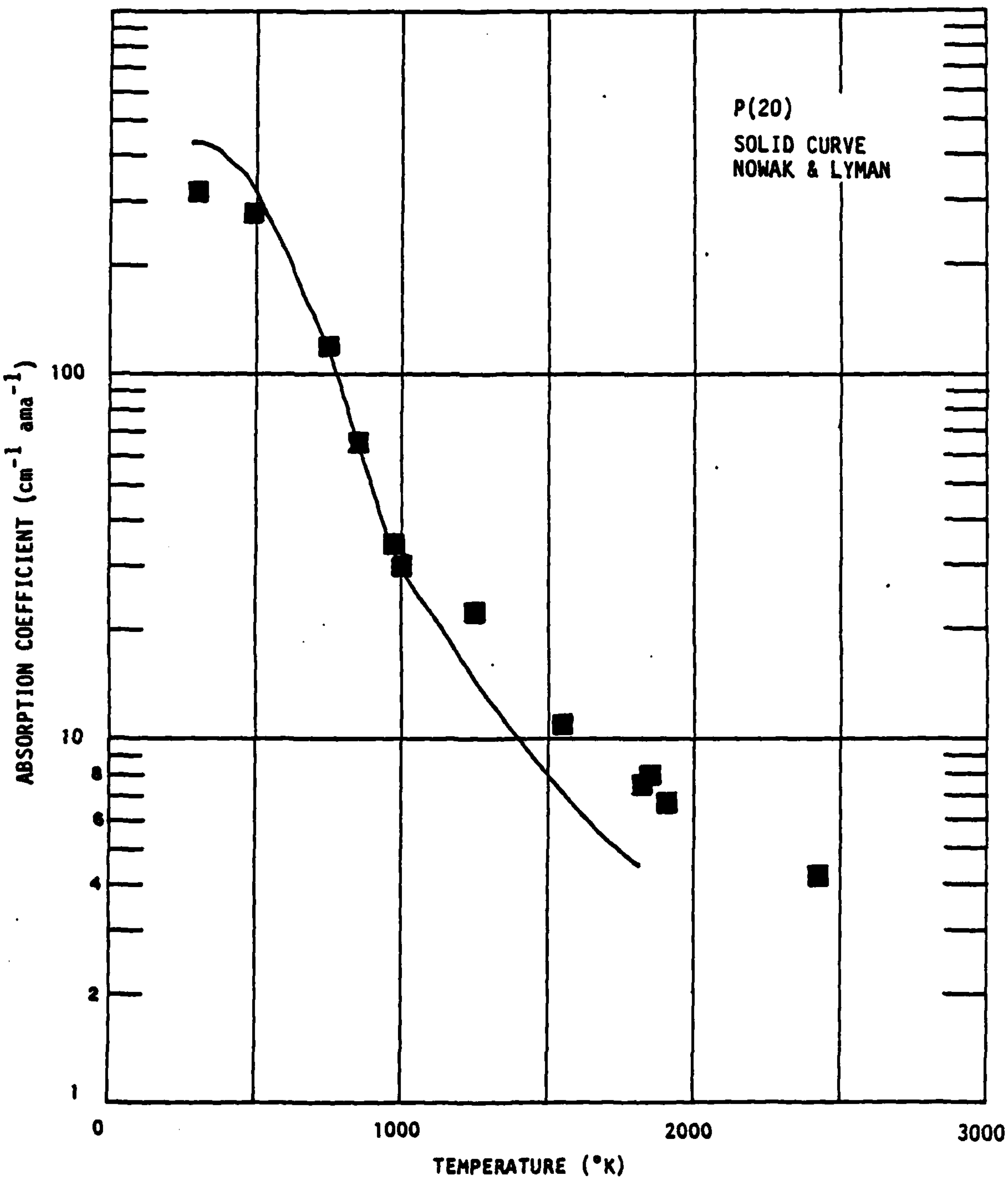


Figure 4. Measured high pressure absorption coefficient of $SF_6$ at the $CO_2$ P(20) laser transition as a function of temperature

Saturation measurements were also made for $SF_6$ but only at room temperature. The absorption coefficient for a single line is specified by:

$$\alpha(\nu) = \frac{\lambda^2 A_{u\ell}}{4\pi^2 c\Delta V_L} F(\nu, \Delta\nu)\left(N_\ell - \frac{g_\ell}{g_u} N_u\right) \tag{1}$$

where $\lambda$ is the transition central wavelength, A is the Einsein Coefficient, $\nu$ is frequency, $\Delta\nu_L$ is line width, c the speed of light, F a line shape function, g is the state degeneracy, and $N_\ell$ and $N_u$ are the populations of the lower and upper states of the transition, respectively. Bleaching occurs when the optical pumping becomes so rapid that the upper state cannot depopulate and thus $N_\ell$ approaches $N_u$. At high pressures bleaching can be crudely modeled by a two-level system and it can be shown to first order that for 10.6 $\mu$m:

$$\alpha \approx \alpha_o \left(\frac{k_q M}{k_q M + 2\alpha_o\left(ama^{-1} - cm^{-1}\right) I\left(W/cm^2\right)}\right) \tag{2}$$

where $\alpha_o$ is the small signal absorption coefficient, I is $CO_2$ laser intensity and $K_q$ is the quenching rate constant for the upper state. As a case in point for $SF_6$ at the P(20) transition and T = 300 K, $\alpha_o \approx$ 300 $ama^{-1}$-$cm^{-1}$ and $k_q$ for Argon is 3 x $10^{-13}$ $cm^3/s$,[2,4] whence for P = 1 atmosphere:

$$\alpha/\alpha_o = 1/2 \text{ at } I = 1.4 \times 10^4 \text{ W/cm}^2 .$$

Saturation measurements performed at one atmosphere in a mix of 0.06 percent $SF_6$/Ar are presented in Figure 5. Shown is the percentage of the laser intensity absorbed across the shock tube for three laser fluences and for $CO_2$ laser transitions P(12) through P(24). Note the laser temporal laser pulse shape is approximately triangular with a pulse time of 0.2 $\mu$s, thus the average intensity is one-half the peak intensity. Clearly the data exhibit significant bleaching effects in the intensity range predicted from Eq. (2). We have located no other atmospheric $SF_6$ bleaching data for comparison with our results.

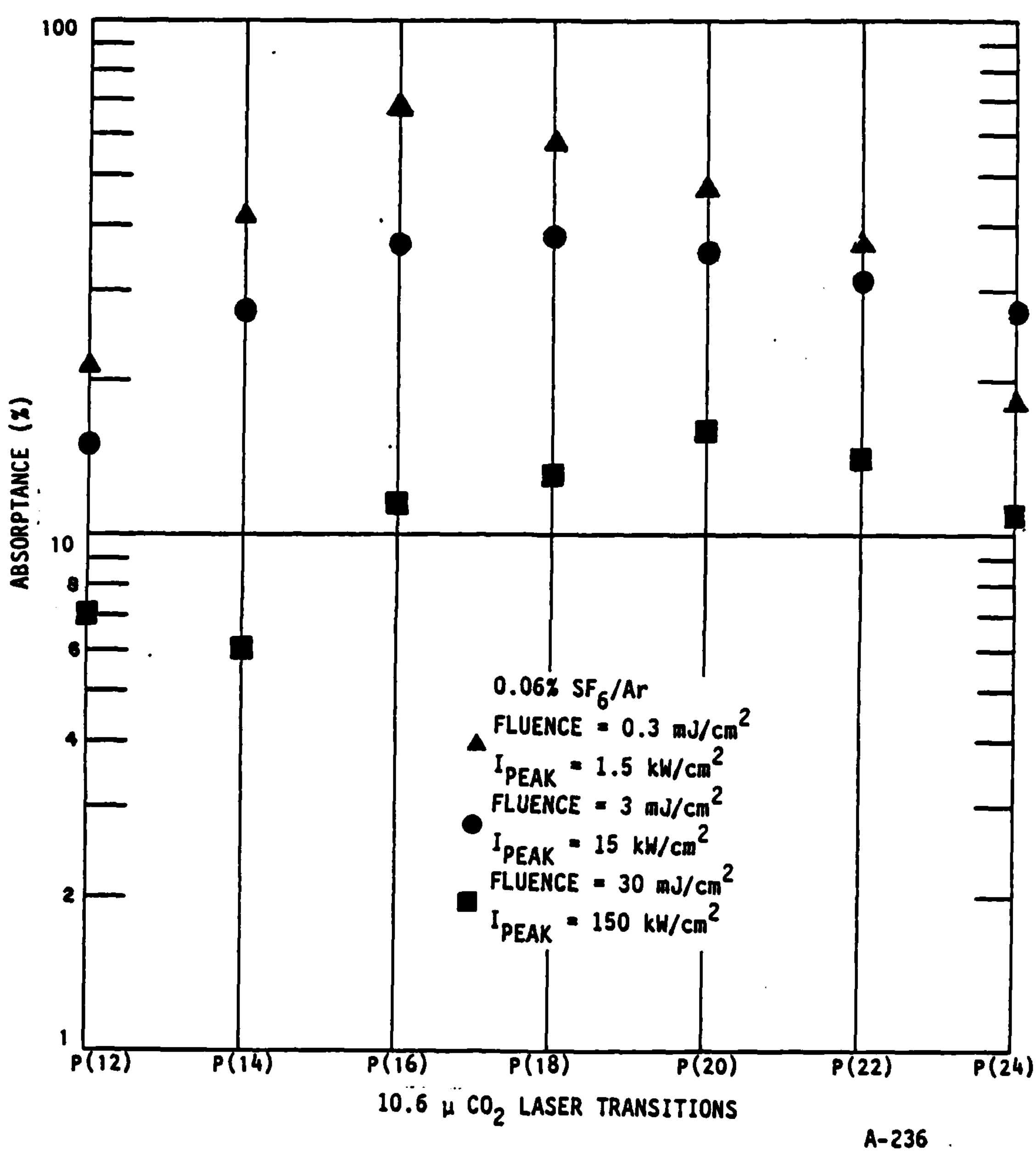


Figure 5. Effect of intensity on $SF_6$ absorption at $CO_2$ laser wavelengths. P = 1 atmosphere, T = 300 K

We next turned our attention to $NF_3$. The $NF_3$ bandhead is to the blue of 10.6 μm and thus we anticipate an absorption coefficient which increases with temperature. There do not appear to have been any previous measurements of the temperature-dependent absorption coefficient of this molecule. Our results for the P(20) transition are shown in Figure 6. Effects due to $NF_3$ decomposition were noted at temperatures above 1200 K and thus absorption coefficients are presented for three different times behind the reflected shock front. The data for 5 μs corresponds to absorption prior to significant $NF_3$ decomposition. Very rapid decomposition, directly behind the shock front, is observed at temperatures beyond ~2000 K.

Interestingly enough equilibrium would predict complete decomposition of $NF_3$ above ~1000 K. Indeed the initial decomposition of $NF_3$ is rapid, the characteristic time for the reaction

$$NF_3 + M \rightarrow NF_2 + F + M \tag{3}$$

is calculated to be 1 μs at $T = 1500$ K and $P = 30$ atm.[2,5] The reason that the absorption coefficient remains high at these temperatures is that $NF_2$ decomposition is much slower,[2,5] and thus as soon as $NF_3$ begins to dissociate, the $NF_2$ concentration hangs up and the reverse of reaction (3) reforms the $NF_3$. This observation has been borne out by detailed kinetic calculations. Thus we see once again that finite rate chemistry can provide for significantly higher absorption coefficients than might be anticipated based on equilibrium expectations.

The last species studied was ammonia. This species, along with water vapor, has been identified as the most promising candidate for the CW propulsion application. Measurements were performed with several mixtures for both linear and "saturated" absorption and the results are summarized in Figure 7. First note the measurements for the two mixtures of $NH_3$ in argon. Comparison between the two sets of data, which span almost a factor of 20 in $NH_3$ concentration, is quite good. Also no difference is observed in absorption coefficient evaluations performed with the pulsed $CO_2$ laser, operating at

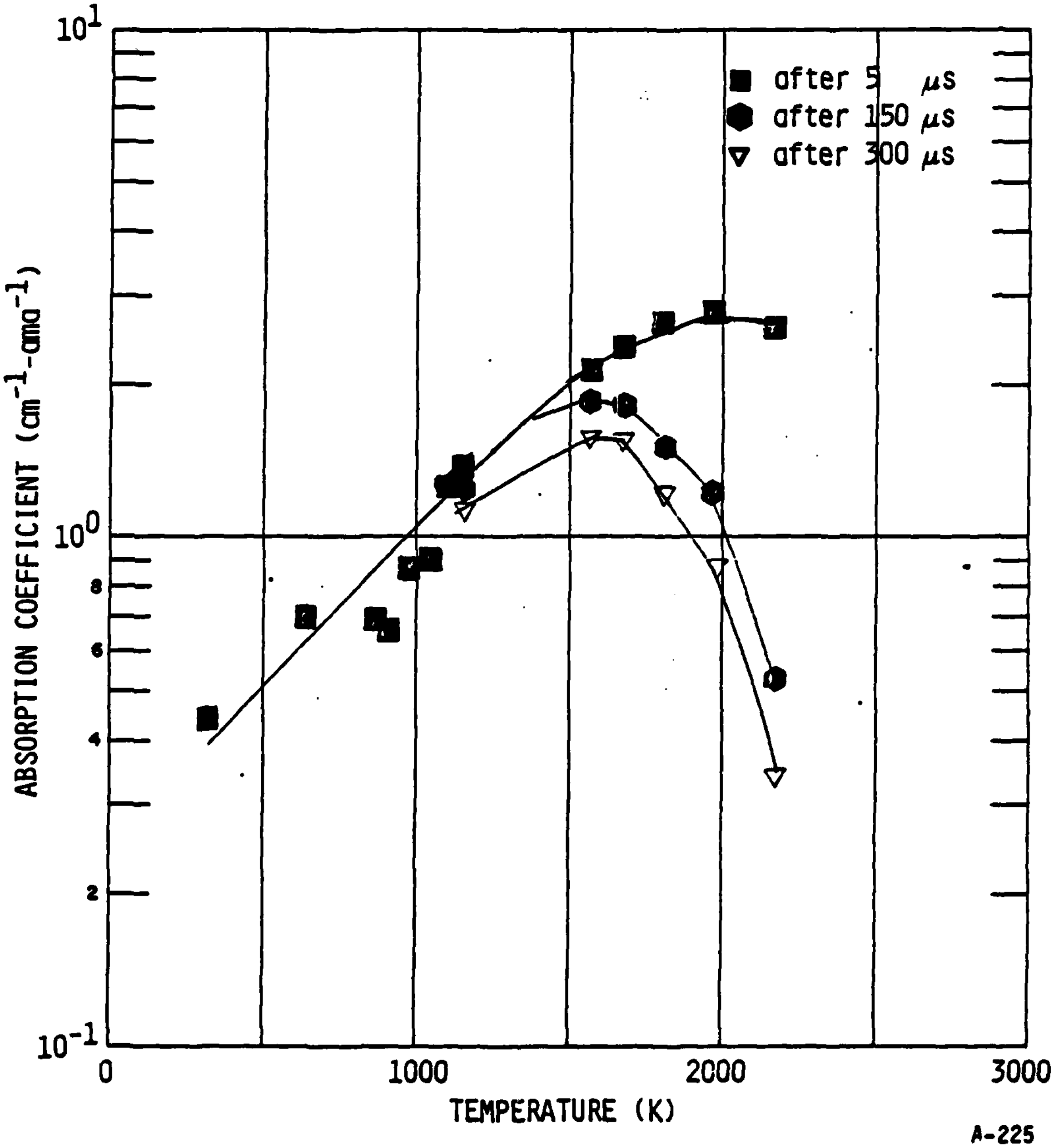


Figure 6. Measured $NF_3$ absorption coefficients in the $CO_2$ P(20) laser transition for several times behind the reflected shock (based on jump condition density and temperature), 3% $NF_3$ in argon

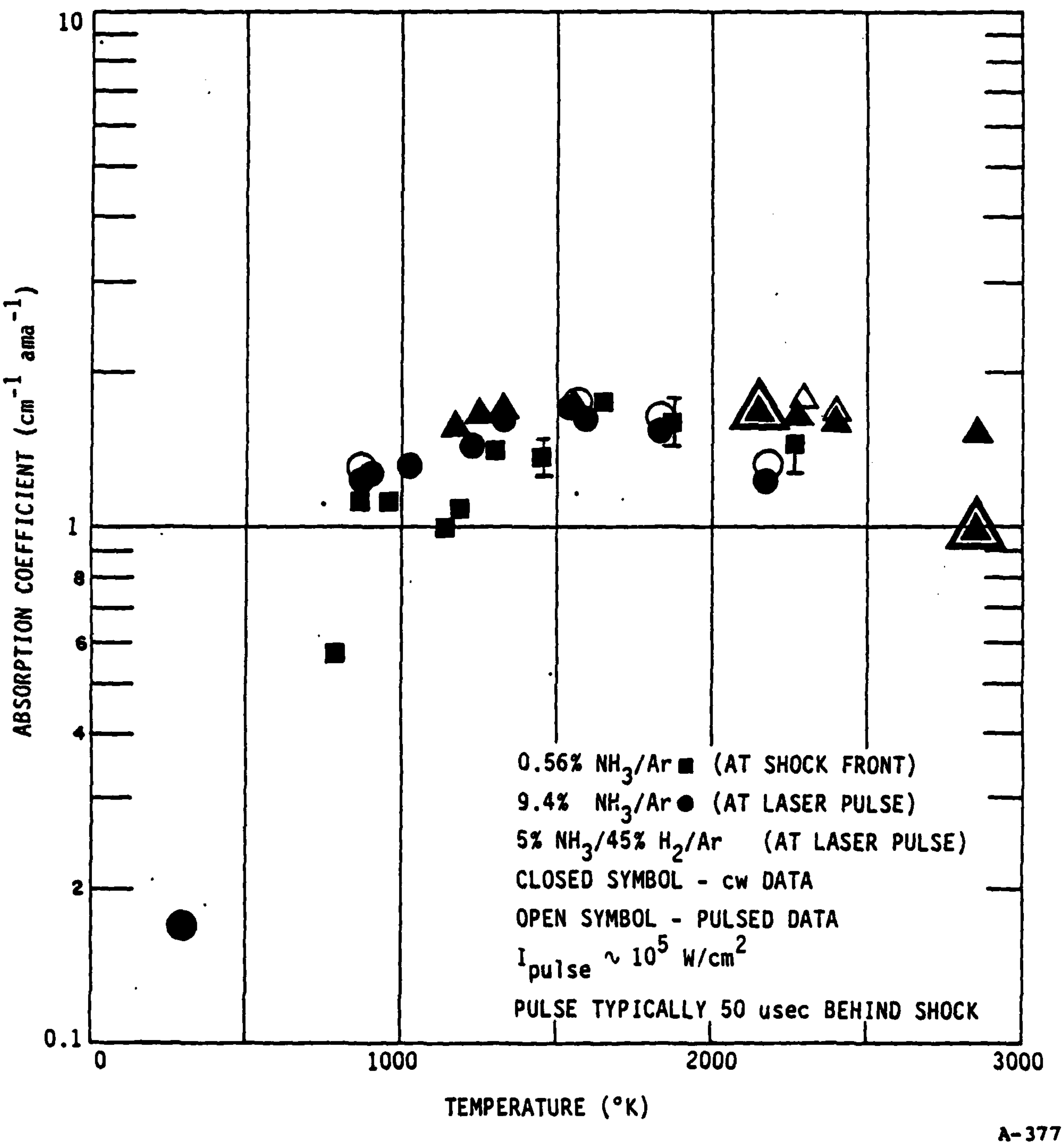


Figure 7. Measured high pressure absorption coefficients for $NH_3$ P(20) $CO_2$ laser transition. No difference is observed between high and low intensity measurements.

typical intensities of $\sim 10^5$ w/cm$^2$. This observation is in line with our expectations as based on Eq. (2) and thus bleaching of ammonia does not appear to be an issue for the CW propulsion application.

One complication with the $NH_3$/Ar observations was that significant decomposition of $NH_3$ became apparent at temperatures exceeding 2000 K. Indeed absorption measurements in these mixes could not be performed at temperatures beyond ~2200 K. We therefore studied absorption in mixes of 5 percent $NH_3$/45 percent $H_2$/50 percent Ar. Hydrogen will most likely be the carrier gas in the CW laser propulsion application and it was anticipated that additional kinetic effects involved by the presence of $H_2$ might prolong the absorption. This was indeed the case as evidenced by the data in Figure 7 where in this instance near constant absorption coefficients were observed out to ~3000 K. This prolongation is the result of the reaction between $NH_2$ and $H_2$ which reforms $NH_3$. Again our observations are in excellent agreement with detailed kinetic predictions.

Lastly it can be seen that the absorption coefficients deduced from $H_2$/Ar mixtures are the same as those observed in an argon carrier, and once again there is no apparent bleaching effect observed.

Our measured absorption coefficients are summarized in Figure 8, normalized by density to emphasize the weight penalty associated with a particular choice. Although both $NF_3$ and $SF_6$ provide attractive absorption potential at low temperature, neither is appropriate for use with an $H_2$ carrier because of chemical reaction. On the other hand, $NH_3$ used in conjunction with $H_2O$ appears to provide an attractive absorber combination for the CW laser propulsion application.

We note that with the exception of $SF_6$ these measurements provide the first evaluation of $CO_2$ laser wavelength absorption coefficients for these molecules at elevated temperatures. Furthermore we have found no previous studies of saturation with which to compare our $SF_6$ and $NH_3$ observations.

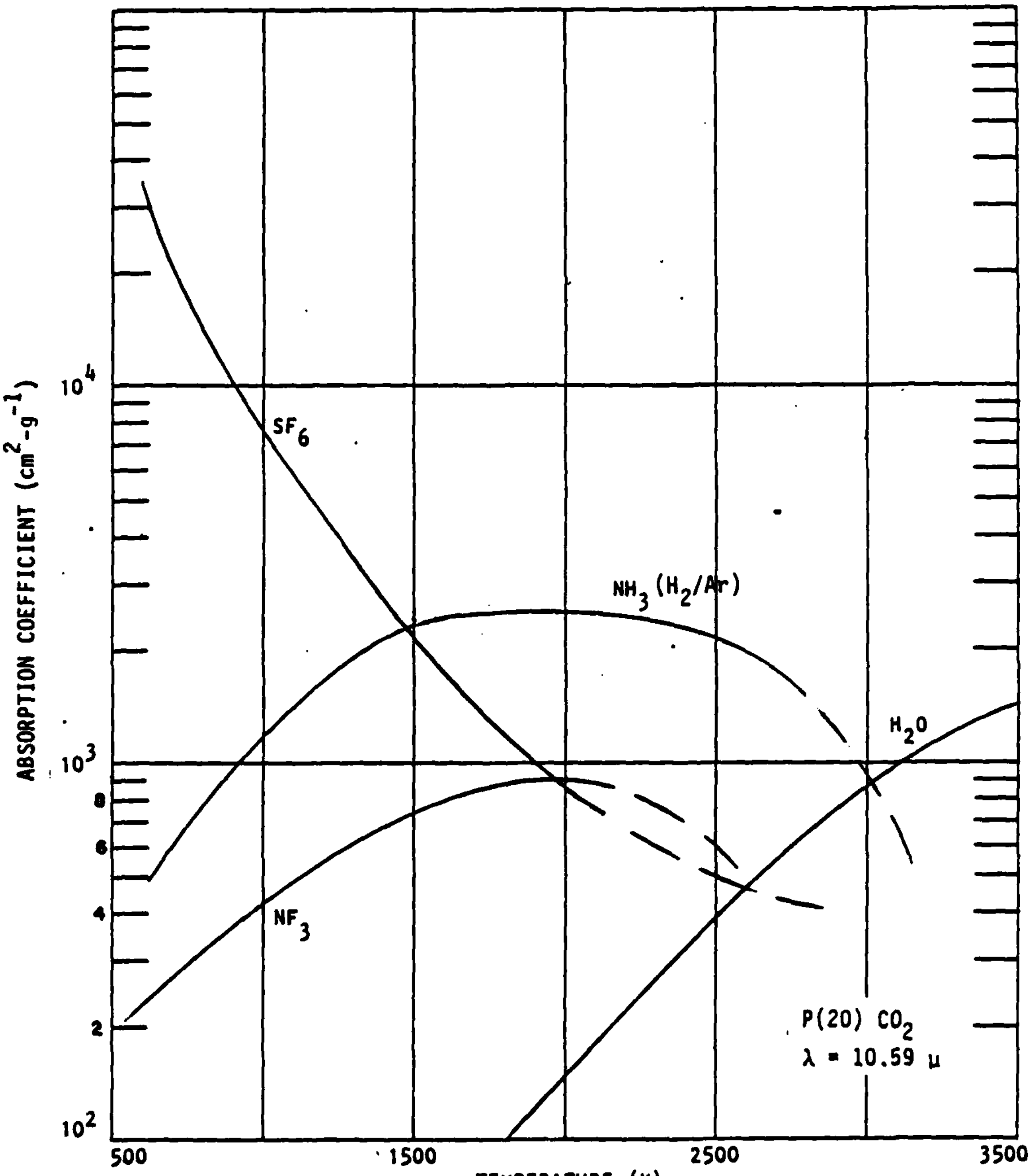


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Figure 8. Experimental high pressure absorption coefficients vs. temperature for potential CW LHT propellants

## 2.2 Experimental and Theoretical Studies of Pulsed Laser/Plasma Absorption (Post-Breakdown Absorption)

The four principal stages in the operation of the pulsed laser-heated thruster were depicted in Figure 2: 1) ignition/breakdown, 2) post-breakdown plasma absorption and growth under the influence of the laser radiation field; 3) blast wave propagation into the surrounding gas, and 4) late-time expansion and cooling of the laser-heated gas. In the previously funded effort we performed experimental and theoretical investigations of laser-induced gas breakdown at short laser wavelengths ($< 1$ μm) for a variety of propellant gas candidates.[2.6] The results of those studies have helped to establish the threshold irradiances required to initiate an optically absorbing plasma and the scaling of those irradiances with gas density, pulse duration, and concentration of low ionization potential additives. With the ignition/breakdown criteria thus established, the next step was to evaluate the subsequent laser energy deposition that occurs in the post-breakdown plasma.

To assure minimal losses due to gas transparency prior to breakdown, it is desirable to operate at fluxes far enough above threshold such that breakdown occurs early in the laser pulse. The remainder of the laser pulse will then be absorbed by way of a laser-driven absorption wave which propagates out from the beam focal volume and ionizes the gas in front of it. The efficiency with which this post-breakdown absorption occurs will, in general, depend upon laser wavelength and intensity, and gas composition and density. For generating high specific impulse, the figure of merit to be maximized is energy deposition per unit mass of propellant.

### Experiments

The experiments we have performed for the current research effort have involved measurements of the laser optical absorption and resulting plasma-dynamics which occurs when high energy pulses of 1.05 μm laser radiation are focused into various gases at focal intensities above the breakdown threshold ($10^{10}$ to $10^{13}$ W/cm$^2$). The extent of laser energy absorption into the gas was determined in two ways: 1) from optical measurements of the laser beam attenuation by the plasma, and 2) from shock trajectory measurements to infer the energy deposited in the laser-driven blast wave.

Shock trajectory information was acquired from high speed photography using a Mach-Zehnder interferometer to probe the laser generated plasma and resulting blast wave. The shock trajectory information obtained from these measurements were used to infer energy deposition information using PSI's quasi-one-dimensional non-steady hydrodynamic code (described below). The gases investigated have included hydrogen and argon.

Plasma optical transmission measurements were also obtained using a large area calorimeter to detect the overall beam energy transmission through the plasma (time-integrated). A schematic diagram of the experiment configuration is shown in Figure 9.

The laser facility we used for these investigations was the high energy glass laser system at Battelle Columbus Laboratories. This laser device is equipped for generating high energy laser pulses at any of three wavelengths,

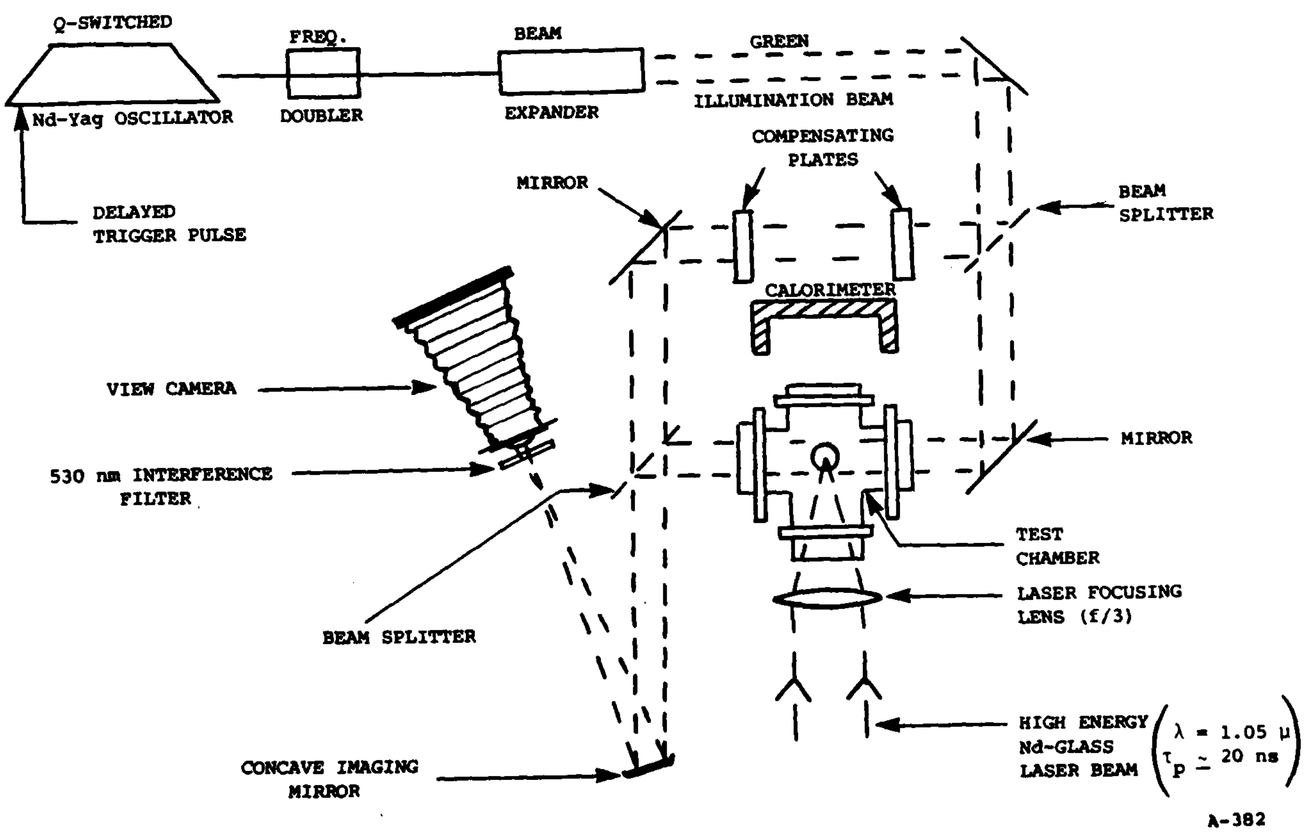


Figure 9. Schematic diagram of experimental setup for laser/plasma absorption measurements

$\lambda$ = 1.05, 0.53, and 0.265 μm. For the present experiments, budgetary constraints have limited us to perform experiments at 1.05 μm only. The available output energy at this wavelength is > 100 J. The nominal output pulse duration of this device is ~20 ns, although longer pulses (up to 80 ns) are also possible. This laser was chosen over the MIT Nd:YAG laser facility because it offers more than a two order of magnitude increase in energy output and, consequently, presents less uncertainties when scaling the results to the full scale interaction. For example, beam focal dimensions can be made sufficiently large such that electron diffusion out of the focal volume is not a concern for the initiation of breakdown.

Prior to the experiments at Battelle, shakedown tests on the various beam and plasma diagnostics were performed at PSI using one of our pulsed $CO_2$ TEA lasers to generate a plasma and a nitrogen-pumped dye laser ($\tau_p \approx$ 5ns) tuned to 530 nm as the interferometer illumination source. These shakedown tests allowed us to test our instrumentation and establish experimental technique. With this approach, the time required at the Battelle facility was minimized.

Optical interferometric techniques to probe laser-produced plasmas and resultant blast waves have been employed previously by numerous investigators (see, for example, review article by A.J. Alcock[2.6]). Briefly, the arrangement used in our experiments was as follows. The laser-produced plasma is created by focusing a high energy Nd-glass laser pulse ($\lambda$ = 1.05 μm, $\tau_p$ = 20 ns) into a cell filled with the test gas of interest. A second, low power, pulsed Nd-YAG laser ($\tau p \approx$ 10 ns), which is Q-switched by means of a Pockels cell and frequency doubled to the green ($\lambda$ = 530 nm), serves as the interferometer light source. This second laser is synchronized with the main laser by receiving a prompt triggering pulse from a photodiode which detects the output pulse of the latter. A variable electronic delay unit is then used to allow "snapshot" interferograms to be taken at selected times after breakdown is initiated. An example of the interferograms obtained in 1 atm of argon is shown in Figure 10. The results clearly show the development and propagation of the laser-driven blast wave. Data of this type were obtained for both hydrogen and argon at various pressures ranging from 0.3 to 10 atm and incident pulse energies varied between approximately 1 and 6J.

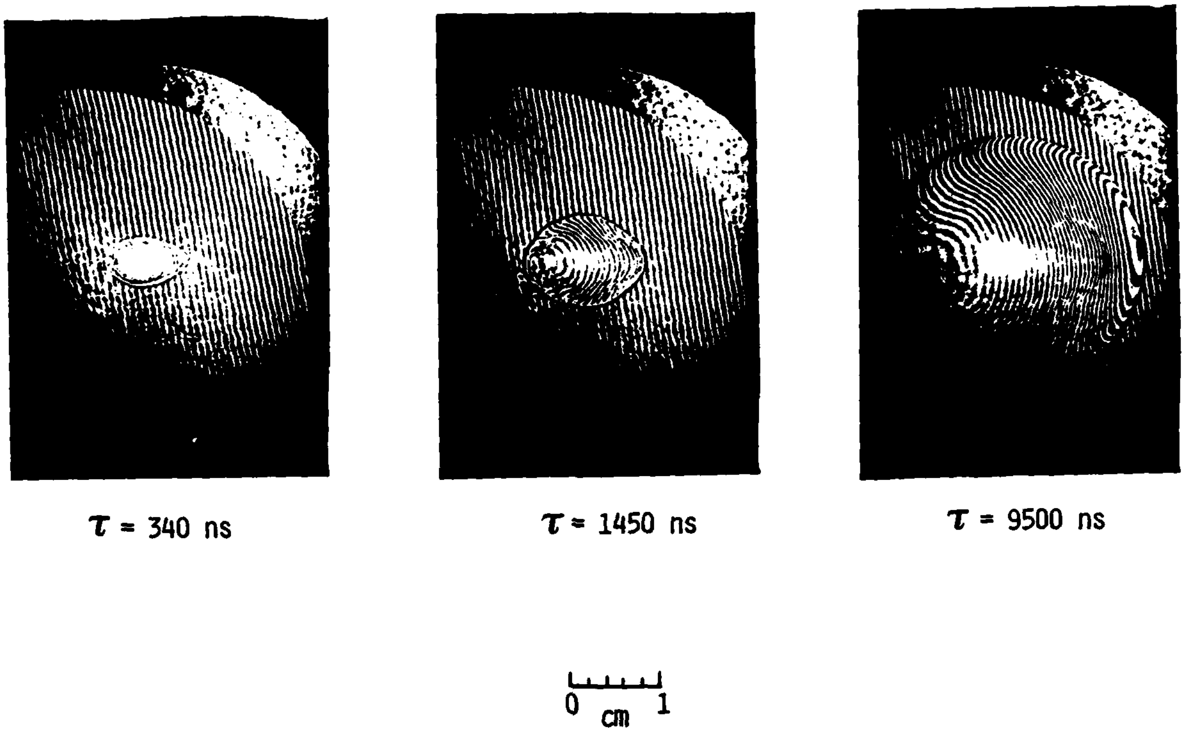


*Figure 10.* Examples of interferograms in one atmosphere of argon showing location of laser-induced blast wave at various times after breakdown. The laser beam was incident from the left, and the blast wave driven by focusing a Nd-glass laser pulse ($\tau_p \approx 20$ ns) with an f/3 lens. The nominal value of the incident pulse energy for these measurements was approximately 2 J.

According to simple blast wave theory it is possible by means of a similarity transformation to reduce to a common curve the measured R-t data for various initial pressures and input energies. For a spherical blast wave propagating in a constant density background,[2.7] this transformation is done according to the relation $R = C\, t^{2/5}$ where $C = (E/\alpha\rho_o)^{1/5}$, E = the energy in the blast wave, $\rho_o$ = the initial gas density and $\alpha$ is a constant that depends on $\gamma$ ($=C_p/C_v$). Thus, by obtaining R-t data from measurements at known initial gas densities, it should be possible to infer the amount of laser energy that was deposited in the blast wave.

Upon examining the interferograms shown in Figure 10, it is apparent that the blast waves generated are aspherical. This is particularly true at the earliest times following laser energy deposition. (This non-sphericity is a result of the anisotropic illumination of the focal region, i.e., f/3 optics, coupled with the finite duration of the laser heating pulse.) To correct for this effect the interferograms taken at the earliest times were generally not used in the analysis. To account for any asphericity that remained at later times, the blast waves were treated as ellipsoid in nature and the radius of an equivalent sphere defined as $R_s = (r_m^2 \cdot r_M)^{1/3}$ where $r_m$ is the minor axis and $r_M$ the major axis of the ellipse.

Figure 11 shows a plot of reduced R-t trajectory data obtained in 1 atm of argon. Shock positions are plotted as a function of reduced time, $t\sqrt{E/\rho_o}$, to account for pulse to pulse variations in the incident laser pulse energy.

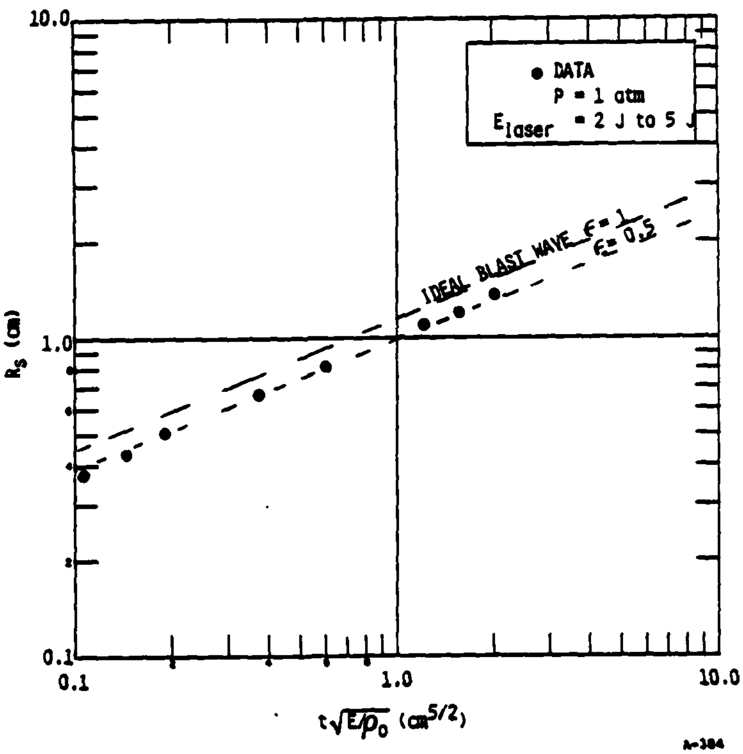


Figure 11. Comparison of argon shock trajectory data with ideal blast wave predictions for 100 and 50% laser to blast wave energy conversion coefficients

It is evident from Figure 11 that the measured R-t shock trajectory data follow rather closely the $R \propto t^{2/5}$ relationship predicted from simple blast wave theory. However, to best fit the data, it appears that a laser to blast wave energy conversion efficiency of only ~50 percent would have to be assumed. This is at odds with the results of the corresponding optical energy transmission measurements which indicate that the fraction of energy absorbed was >95 percent. Similar discrepancies were found when applying the simplified blast wave analysis to other trajectory data (in hydrogen as well as in argon).

Concerned with the inadequacies of applying the simplified blast wave analysis to the data, we decided to perform more detailed calculations using PSI's LSDNS computer code.[2.8,2.9] The computer model allows us to treat in one calculation some key phenomena not included in the simple blast wave analysis. These include: 1) the importance of 'real' gas effects (i.e., ionization, dissociation, electronic excitation) in tying up energy that is then unavailable to drive shock motion; 2) the transition at late times from strong shock to weak shock hydrodynamics; and 3) energy deposition in a finite initial volume.

## Theoretical Support for Plasma Absorption Experiments

PSI has a computer code (LSDNS) which calculates the nonsteady quasi-one-dimensional flow of a real equilibrium gas. The code operates in two modes: 1) the blast wave mode, and 2) the absorption mode.

In the blast wave mode, the calculation starts with the laser energy already absorbed in a small region of the gas. The code then calculates the evolution of the gas flow including the propagation of the blast wave which forms.

In the absorption mode, the calculation starts with a small amount of energy deposited in a very small region of gas, in order to initiate absorption. The code then calculates the further absorption of laser energy, and the gas flow, including the propagation of the LSD wave which results from the absorption.

A description of the development of the code is given in Chapter 3 of Ref. 2.8, including the absorption coefficients and the thermodynamics for argon and hydrogen.

This computer code was used to perform supporting analyses for the plasma absorption experiments. Calculations in the absorption mode are being performed for the same cases studied in the experiment to compare the amount of energy absorbed with that observed. In the blast wave mode, the motion of the wave has been calculated and compared with the experimental observations to infer the amount of energy deposited.

Preliminary Results

Figure 12 compares the trajectory results shown in Figure 11 with the corresponding predictions of LSDNS calculations for real argon. As can be seen there is good agreement between the computed trajectory and the measurements. This was achieved using a laser energy deposition efficiency of unity rather than 0.5 -- in better agreement with the laser energy transmission measurements.

Figure 13 summarizes the results obtained for the fraction of laser energy that was deposited in argon and hydrogen. Plotted are the deposition efficiencies indicated by the optical energy transmission measurements (solid circles) and those inferred from the shock trajectory data using PSI's LSDNS code. For the latter, the x's indicate the results obtained with the assumption of perfect gas behavior, i.e., $\gamma = 1.4$ and 1.67 for hydrogen and argon respectively, and the arrow heads (↑) indicate the results obtained when real gas thermodynamics are used. It is apparent that the inclusion of real gas thermochemistry has a significant effect on the inferred blast wave energy and leads to considerably better agreement with the optical transmission measurements.

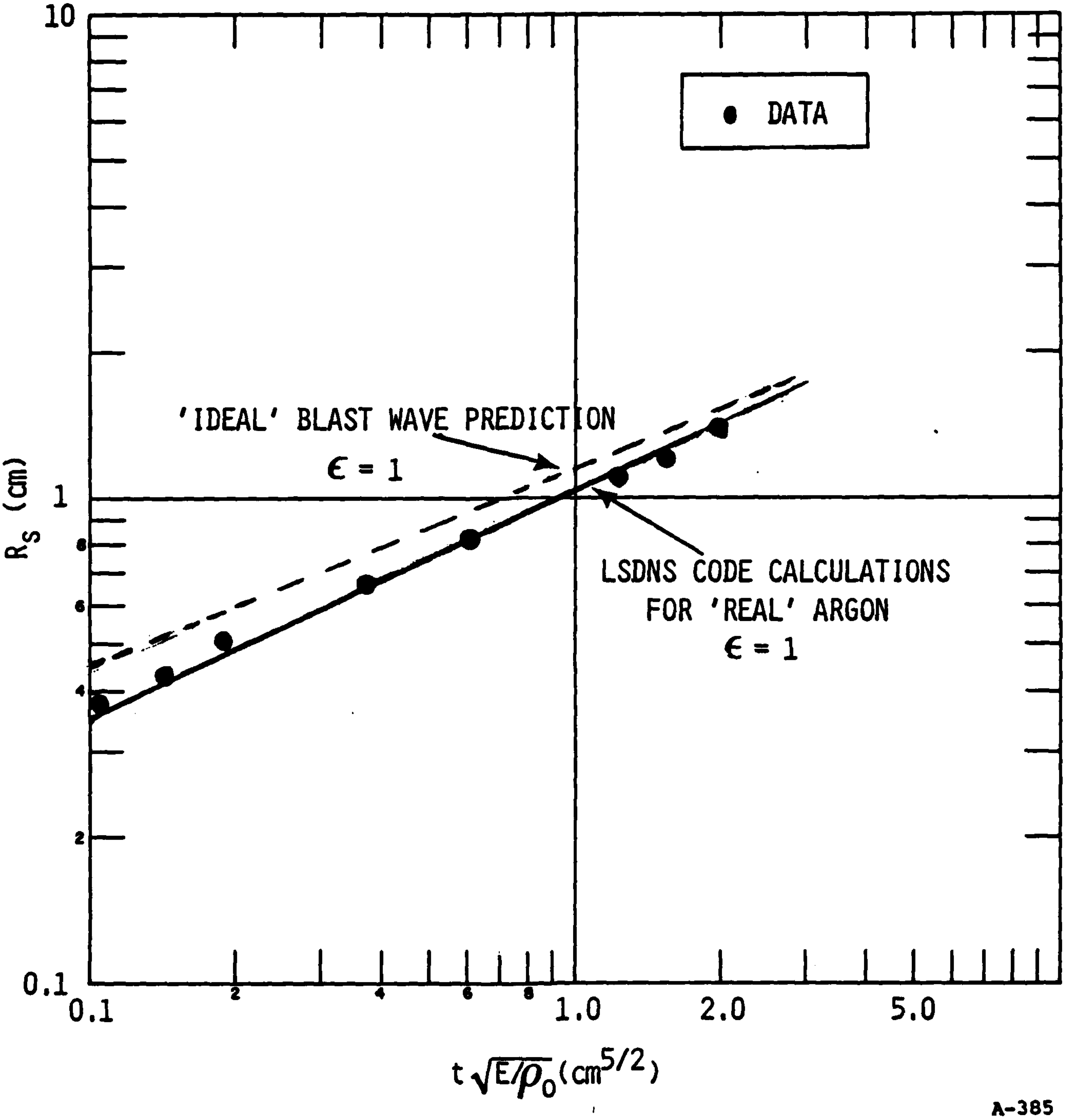


Figure 12. Comparison of blast wave trajectory data in 1 atm argon with 'ideal' blast wave prediction and detailed LSDNS code calculations that include 'real' gas effects

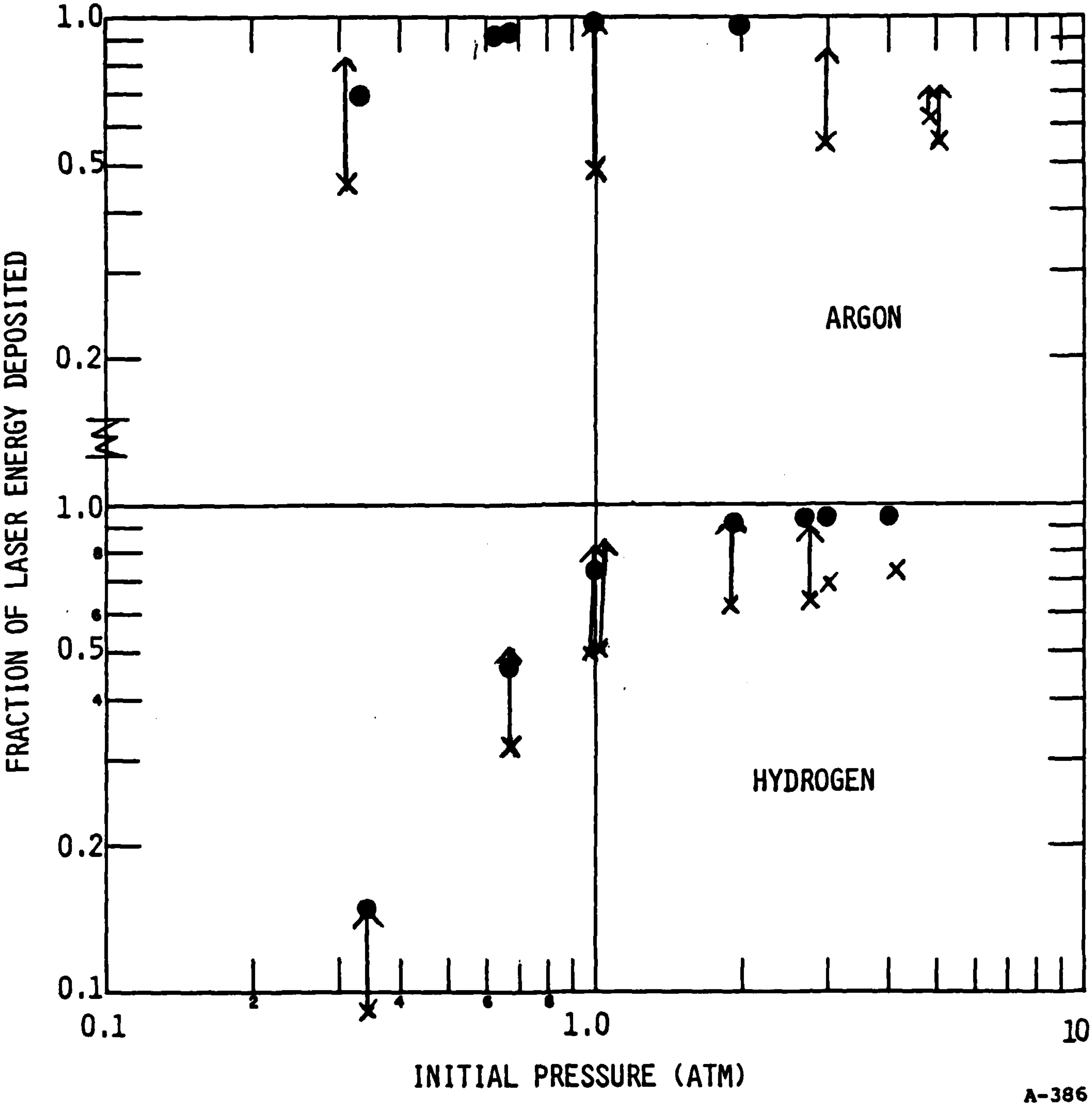


Figure 13. Results of laser energy deposition measurements in argon and hydrogen. ● - from optical transmission measurements, x - from "blast wave:" analysis without real gas effects, and ↑ - from "blast wave" analysis including real gas effects.

Thus, while the analysis is not yet final, the results clearly have important implications. Perhaps the most important is that they demonstrate that conversion efficiencies of pulsed laser energy to blast wave energy approaching 100 percent can be achieved in candidate propellant gases. The results also suggest that there is likely to be an optimum gas pressure or density at which to deposit the laser energy. For example, in hydrogen the fall-off in the absorption efficiency with decreasing pressure that is seen in Figure 13 is undoubtedly the result of the increased time to ignition that occurs at lower pressures and, hence, increased transparent losses prior to breakdown. Additional detailed analysis and discussion of these results will follow in a future scientific report.

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## 3. WRITTEN PUBLICATIONS IN TECHNICAL JOURNALS

1. "Laser-Induced Breakdown in Argon at 0.35 micrometer - Theory and Experiment," Guy M. Weyl and David I. Rosen, accepted for publication in Physical Review A (to be published April 1985).

2. "Computer Simulation of the Non-Steady Flow of a Real Gas with Laser Energy Absorption," Nelson H. Kemp - submitted for publication in AIAA Journal.

3. "Absorption of $CO_2$ Laser Radiation in Hot $SF_6$, $NF_3$, and $NH_3$," Robert H. Krech, Lauren M. Cowles, George E. Caledonia, and David I. Rosen - Paper No. 54 accepted for presentation at 15th International Symposium on Shock Waves and Shock Tubes (July 29 - August 1, 1985). Written paper to be published in the proceedings volume.

## 4. LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT

Dr. David I. Rosen - Program Manager and Principal Investigator for pulsed laser/plasma absorption experiments

Mr. George E. Caledonia - Principal Investigator for high temperature molecular absorption studies

Dr. Nelson H. Kemp - Principal Scientist responsible for modeling of pulsed laser-driven flows

Mr. Robert H. Krech - Chief Experimentalist responsible for carrying out shock tube absorption experiments.

## 5. INTERACTIONS (COUPLING ACTIVITIES)

- Two spoken papers at 1985 AFOSR/AFRPL Rocket Propulsion Research Meeting, 18-21 March 1985, Lancaster, CA.
  - "Linear and Saturated Absorption of Laser Radiation in Heated Gases," Robert H. Krech, Lauren M. Cowles, George E. Caledonia, and David I. Rosen
  - "Energy Deposition of Pulsed One Micron Laser Radiation in Hydrogen and Argon," David I. Rosen, Nelson H. Kemp, and Henry Murphy
- Spoken paper entitled "Laser Propulsion," authored by Nelson H. Kemp and David I. Rosen and presented at Joint Propulsion Conference, June 13, 1984, Cincinatti, OH
- Spoken paper, "Computer Simulation of the Non-Steady Flow of a Real Gas with Laser Energy Absorption," by Nelson H. Kemp. Presented at AIAA 17th Fluid Dynamics, Plasma Dynamics, and Lasers Conference, June 25-27, 1984, Snowmass, CO.

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